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# THE STRENGTH OF THE EARTH'S CRUST

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## PART VI. RELATIONS OF ISOSTATIC MOVEMENTS TO A SPHERE OF WEAKNESS—THE ASTHENOSPHERE.<sup>1</sup>

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### INTRODUCTION AND SUMMARY

In studies on the nature of isostasy it is necessary to distinguish between, first, the existence of isostasy; second, the limits of isostatic equilibrium; and third, the mode of maintenance of this equilibrium.

The first has long been known, the knowledge of the existence of some relation of density counterbalancing elevation having been gradually developed since the middle of the nineteenth century through the determination of the local deviations of the vertical as shown by the comparison of the astronomic and geodetic latitudes for the same station. This was a problem which arose in both astronomy and geodesy. It was found, when the attractive effect of the mountain regions was computed, that they did not deflect the vertical at adjacent stations as much as was to be expected from their visible masses. The phenomenon was first pointed out

<sup>1</sup> An abstract of Parts V, VI, and VII of this series was given at the April, 1914, meeting of the American Philosophical Society at Philadelphia under the title, "Relations of Isostasy to a Zone of Weakness—the Asthenosphere." See *Science*, XXXIX, 842.

by Petit in 1849.<sup>1</sup> Archdeacon Pratt of Calcutta showed a few years later that whereas a discrepancy of 5.2'' existed between the geodetic and astronomic latitudes of Kalianpur and Kaliana, the calculation of the effect of the Himalayas called for a difference of 15.9''.<sup>2</sup>

These facts were definitely formulated into a theory of isostasy by the Astronomer Royal of Great Britain, G. B. Airy, within a year following the appearance of Pratt's paper,<sup>3</sup> though it remained for Dutton to recognize the large geologic significance and to coin for the relations of elevation and density the word isostasy.<sup>4</sup> Following this Putnam and Gilbert showed by gravity measurements that a considerable degree of regional isostasy existed over the United States.<sup>5</sup> Since then has appeared the much more detailed work of Hayford and Bowie, the computations made by the computing office of the United States Coast and Geodetic Survey under their directions making possible this present investigation.

Thus there has developed through more than half a century evidence beyond controversy which shows that the earth's crust in its larger relief and, within certain limits, even its smaller features, such as the great plateaus and basins, rests more or less approximately in flotation equilibrium.

The second division of the larger problem of isostasy, that of the areal limits and degree of perfection of isostatic adjustment, is the subject which has been dealt with in the previous parts of this investigation. It has been found that, although the relations of continents and ocean basins show with respect to each other a high

<sup>1</sup> "Sur la latitude de l'Observatoire de Toulouse, la densité moyenne de la Chaîne des Pyrénées, et la probabilité qu'il existe un vide sous cette chaîne," *Comptes rendus de l'Acad. des Sc.*, XXIX (1849), 730.

<sup>2</sup> "On the Attraction of the Himalaya Mountains and of the Elevated Regions beyond Them, upon the Plumbline in India," *Phil. Trans. Roy. Soc.*, Vol. CXLV (1855).

<sup>3</sup> G. B. Airy, "On the Computation of the Effect of the Attraction of Mountain Masses as Disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys," *Phil. Trans. Roy. Soc.*, Vol. CXLV (1855).

<sup>4</sup> "On Some of the Greater Problems of Physical Geology," *Bull. Phil. Soc. Wash.*, XI (1889), 53.

<sup>5</sup> *Bull. Phil. Soc. Wash.*, XIII (1895), 31-75.

degree of isostasy, there is but little such adjustment within areas 200 to 300 km. in diameter, or of limited differential relief. Individual mountains and mountain ranges may stand by virtue of the rigidity of the crust. Even under the level plains equally great loads are permanently borne, loads produced by widespread irregularities of density not in accord with the topography above. Isostasy, then, is nearly perfect, or is very imperfect, or even non-existent, according to the size and relief of the area considered.

The third division, the mode of maintenance of isostasy and its bearings on problems of the crust, remains to be considered. This condition of isostatic equilibrium exists at present in spite of the leveling surface actions and compressive crustal movements of all past geologic time. There must be, consequently, some internal mode of restoring more or less perfectly an isostatic condition, either by frequent small movements, or by more infrequent and larger ones.

Erosion and sedimentation result in a lateral transfer of matter, and to maintain isostasy there must be some lateral counter-movement in the earth below, but in regard to how or where or when this is done, and as to what are its effects, there has been no unanimity of opinion, nor convincing demonstration.

In considering the problems of crustal dynamics some authors have regarded earth shrinkage and consequent tangentially compressive forces as controlling the nature of diastrophism, including movements of both orogenic and epeirogenic character; others, the advocates of extreme isostasy, have thought to see even in folding only the secondary effects of movements maintaining isostatic equilibrium. The first point of view emphasizes the strength and elasticity of the crust, with long-deferred periodic discharge of stress. The second point of view calls for an interpretation based on the weakness and plasticity of the crust, with resulting nearly continuous small movements restoring the delicate vertical balance destroyed by gradational actions. To what degree are the two points of view compatible and within what limits is each dominant? The problem of this chapter involves, therefore, not only the mode but the limits and effects of the movements which more or less completely maintain or restore isostasy.

The method of attack is largely one of exclusion. By showing what hypotheses cannot apply, the way is prepared for conclusions in better accord with the fields of fact and theory.

The results show that conditions of isostatic equilibrium cause the light and high segments to press heavily against the adjacent lower and heavier ones, most heavily above. The tendency is consequently for the high areas to spread with a glacier-like flow over the low areas. This tendency, however, is effectively resisted by the strength of the crust. Upon the disturbance of equilibrium by erosion and deposition there are two kinds of stresses produced which tend to restore equilibrium. The first is a tendency of the heavy column to underthrust the lighter, but it could never produce compression and folding at the surface. This force would be most effective under the hypothesis of great crustal weakness, so that the vertical stresses could be transmitted in a horizontal direction within the lithosphere as in a fluid. Even in that case, however, it would not be the dominating force. The actual isostatic movements consist of a rising of the eroded areas, a sinking of those which are loaded. This involves shear or flexure around their boundaries. The columns must be large enough so that the excess or deficiency of mass can become effective in producing deformation. When the accumulating vertical stresses have overcome the strength of the crust, the excess pressure from the heavy area is transmitted to the zone below the level of compensation. This deep zone is in turn the hydraulic agent which converts the gravity of the excess of matter in the heavy column into a force acting upward against the lighter column and thus deforms the crust of the eroded area. By this means even the continental interiors are kept in isostatic equilibrium with the distant ocean basins. This implies a great depth and thickness to the zone of plastic flow. Although it must be plastic under moderate permanent stresses, this does not imply by any means a necessarily fluid condition, and fluidity is disproved by other lines of evidence.

The zone of compensation, being competent to sustain the stresses imposed by the topography and its isostatic compensation, must obey the laws pertaining to the elasticity of the solid state and is to be regarded therefore as of the nature of rock. Consequently there may be extended to all of it the name of the litho-

sphere, even though it includes from time to time molten bodies, the constituents of the pyrosphere.

The theory of isostasy shows that below the lithosphere there exists in contradistinction a thick earth-shell marked by a capacity to yield readily to long-enduring strains of limited magnitude. But if such a zone exists it must exercise a fundamental control in terrestrial mechanics, in deformations of both vertical and tangential nature. It is a real zone between the lithosphere above and the centrosphere below, both of which possess the strength to bear, without yielding, large and long-enduring strains. Its reality is not lessened because it blends on the limits into these neighboring spheres, nor because its limits will vary to some degree with the nature of the stresses brought upon it and to a large degree by the awakening and ascent of regional igneous activity. To give proper emphasis and avoid the repetition of descriptive clauses it needs a distinctive name. It may be the generating zone of the pyrosphere; it may be a sphere of unstable state, but this to a larger extent is hypothesis and the reason for choosing a name rests upon the definite part it seems to play in crustal dynamics. Its comparative weakness is in that connection its distinctive feature. It may then be called the sphere of weakness—the *asthenosphere*, and its position among the successive shells which make up the body of the earth is as follows:

The atmosphere	}	Including the biosphere
The hydrosphere		
The lithosphere	}	Including the pyrosphere
The asthenosphere		
The centrosphere, or barysphere		

Each has played its fundamental part in the development of earth-history.

#### STRESS-DIFFERENCES BETWEEN CONTIGUOUS COLUMNS OF THE CRUST

*Stresses under conditions of isostatic equilibrium.*—The continental platforms slope down into the ocean basins at grades which range mostly from one in ten to one in thirty. Some of the great

foredeeps show both the greatest depths of water and the steepest descents. The Chilean coast, for instance, at lat.  $25^{\circ}$  S., slopes from the Andes to a depth of 7,500 meters with a submarine grade of one in eight. Under the hypothesis of nearly perfect isostasy, which will be favored in this discussion, this would be taken to show the contiguity of areas in the crust of markedly unlike density.

Let the slope between such areas be regarded as a thick partition between two columns, each in isostatic equilibrium. These rest then upon the substratum below the zone of compensation with the same pressure and stand vertically in equilibrium.

In so far as the rock within the crust is subjected to mere cubic compression, equal in all directions and increasing with depth, there is no distortional force. In so far, however, as side pressures in one column are not balanced by equal side pressures from the adjacent columns, there is a stress-difference which does produce a distortional strain. If the stress-difference exceeds the elastic limit a permanent deformation results which reduces the stress and eases the strain. It is the plan of this paper to discuss the nature of the stress-differences on the partition separating two contiguous columns of the crust, of markedly unlike density; first, when these are in isostatic equilibrium, and second, when not in such equilibrium. Fig. 13 is drawn to show graphically these relations.

The land-column of the crust is marked *M*; the submarine column is *N*; *O* is the earth-shell below the zone of isostatic compensation; *P* is the column of sea-water. The vertical partition between the unlike columns stops in reality, according to the hypothesis, at the bottom of the columns. It is here extended down through the earth-shell *O-O* in order to discuss the deformation which would take place in the latter shell. *M* and *N* represent what is here called the lithosphere; *O-O* the zone which it is proposed to call the asthenosphere.

In case A, isostatic equilibrium is assumed and the pressures of the two lithospheric columns are equal upon the asthenosphere. But, assuming for the moment that the vertical pressures are freely transmitted as lateral pressures, it is seen that a marked horizontal unbalanced pressure is produced by the land-column against the

sea-column, as represented by the horizontal lines of the stress diagram. The top of the land-column is balanced only against the negligible weight of the atmosphere and the lateral stress gradient is there highest. The next portion below is balanced against the

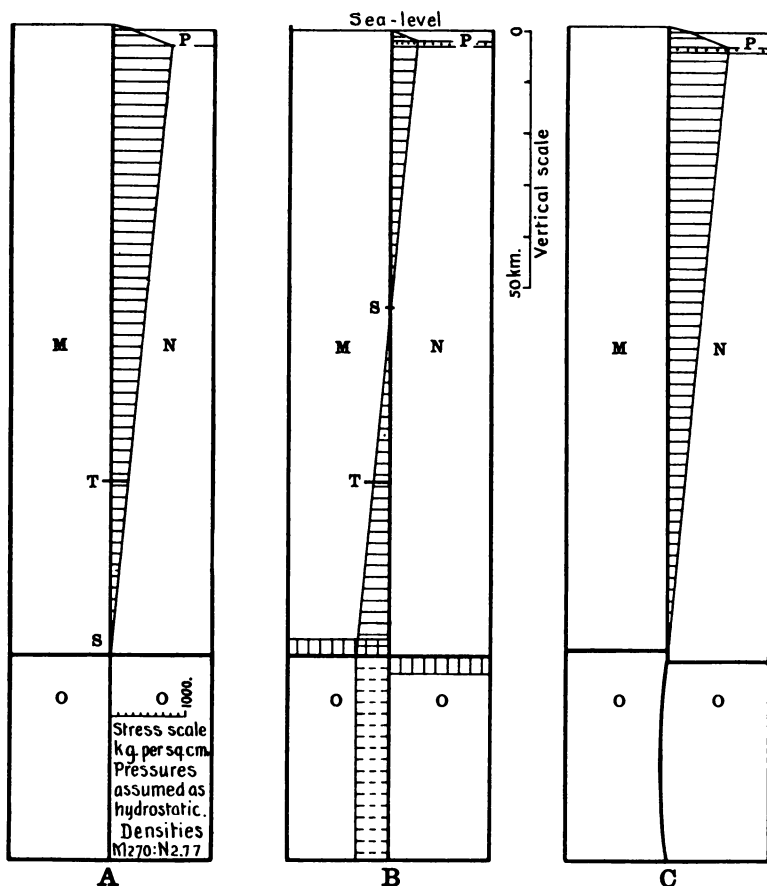


FIG. 13.—Diagram illustrating pressure-relations of the crust for marginal portions of the continental shelf and oceanic basin, interpreted as balanced by uniformly distributed isostatic compensation. Stress-differences are shown by cross-lined diagrams, the pressures being regarded as transmitted hydrostatically. The actual lateral stress-differences, for stresses within the elastic limit, are about one-fourth of the hydrostatic pressures here shown.

- A. Columns in isostatic equilibrium.
- B. Relations after base-leveling.
- C. Relations after re-establishment of isostatic equilibrium.



sea-water and the stress gradient becomes less high. The maximum thrust occurs at the bottom of the ocean and is from the land toward the sea. Below this level the density of the sea-column is greater than that of the land-column. This, with increasing depth, gradually balances the excess pressure, and at the base of the lithosphere both the lateral and vertical pressures of both columns by hypothesis are equal.

In this diagram the pressures of the columns are imagined to act hydrostatically, but, in reality, for stresses *within the elastic limit*, this would not be so. Further, in so far as the partition is much wider than the difference in elevation of the columns, it has a gentle surface slope and will tend to give the upper part of the land-column competence to hold itself in by its own strength and that of the partition. The approximate ratio which the actual lateral pressure-differences on the two sides of the partition hold to the assumed hydrostatic pressures may be perceived from the results of a recent work by Love entitled *Some Problems of Geodynamics*.<sup>1</sup> In chaps. ii and iii he considers the problems of the isostatic support of continents and mountains. As a basis for the analytic treatment he assumes, first, the existence of complete compensation within a depth of one-fiftieth of the earth's radius, 127 km.; second, that at this depth all stress-differences disappear, the pressures below being of the nature of hydrostatic pressures, the only kind which could occur if a fluid layer existed at and below the depth of 127 km.; third, it is known that the heterogeneities of mass in the lithosphere only slightly modify the form of the geoid, and it is accordingly assumed that there is no such effect. Love thus treats of the limiting case of a crust exhibiting perfect isostasy, its surface relief not modifying the form of the geoid given by the ocean surface, and resting with its base upon a fluid zone. As such, his solution is of great value, but he states: "It must, however, be understood that the special form (of the hypothesis of isostasy) is introduced for the sake of analytical simplicity rather than physical appropriateness."<sup>2</sup>

The artificiality of the assumption of the existence of no stress-differences below the zone of compensation is shown by the law of

<sup>1</sup> Cambridge University Press, 1911.

<sup>2</sup> *Op cit.*, p. 7.

density distribution which results. With only these three limiting assumptions, the number of unknown quantities remains larger than the number of equations, and the results are, strictly speaking, indeterminate; but by making various reasonable further assumptions definite solutions in accordance with these may be obtained. The elimination of stress-differences at the base of the lithosphere, taken as equivalent here to the zone of compensation, requires, however, that there shall be a peculiar relation of densities. To compensate an elevation it must be offset by matter below of less density than the mean for that depth, but in order to quench the stress-differences at the base of the lithosphere there must be between the light matter and this base a layer of more than mean density for that depth. Thus the light layer must perform a two-fold function, compensating not only the elevation above but the heavy layer below. For depressions in the crust there must be a reverse arrangement, matter of more than mean density existing immediately below the surface. But above the base of the lithosphere there must be a layer of less than mean density for that depth. The artificialities of this scheme would be sufficient to form a disproof of the initial assumption which determined it, but it also seems to be directly disproved by the evidence brought forward in the earlier parts of the present article. Nevertheless, the exact mathematical solution of this difficult problem is of great value as giving the results of the assumptions of extreme isostasy.

For the largest inequality of the crust, regarded as a zonal harmonic of the first order, that represented by the land and water hemispheres, Love shows that the lateral stress-differences under this hypothesis of isostasy reach a maximum at a depth equal to one-third of the zone of compensation and are equal to only 0.006 of the weight of a column of rock of height equal to the maximum height of the inequality. For harmonics of the second and third orders, representing the continents, the fractions are 0.0134 and 0.0208. These results, Love states, are extremely favorable to the hypothesis of isostasy, since the inequalities could be supported by any reasonably strong material.

There are two criticisms, however, to be noted while citing this conclusion. First, it is known that the crust is vastly stronger than

these requirements, so that such a perfected isostatic arrangement is not demanded on the score of crustal weakness. Second, the harmonic curves giving these figures are of a gently sweeping character; whereas, the actual continents are in many places high on their margins, and from these margins they slope with comparative steepness to the mean depth of the ocean floors. The stresses set up beneath the continental margins are accordingly a closer approximation to those imposed by lofty mountain ranges. Assume that compensations of the continental margins are perfect and the problem becomes that which Love takes up in the following chapter, namely, the isostatic support of mountains, except that we deal with only one great slope, whereas the theory calls for a succession of mountains and valleys.

It is shown that for such a compensated series, postulating the distribution of densities previously discussed, the greatest stress-difference exists at the mean surface, beneath the crests, and reaches a value equal to half the weight of a column of rock equal to half the height of the crests above the valley bottoms. From this maximum the stress-difference decreases to zero at the base of the zone of compensation. The solution by G. H. Darwin for uncompensated mountains and valleys gave a maximum stress-difference equal to 74 per cent of half the height, this maximum occurring at a depth equal to about one-sixth the distance between mountain crests. Even with perfect isostatic compensation, distributed after the fashion assumed by Love, the stress-differences for mountains and valleys are seen consequently to be two-thirds in value of those produced by an uncompensated relief, and are approximately one-fourth of the hydrostatic pressures. This fraction, one-fourth, happens also to be the same as Poisson's ratio, the ratio of the lateral expansion to the vertical shortening of a free rock column under vertical stress.

Now the distribution of density has been found to be more or less irregular, and there is no evidence of such a reversing layer at the base as Love has postulated. Stress-differences will consequently extend below the isostatic compensation. If, however, the latter is not uniformly distributed, but is concentrated somewhat in the outer half of the lithosphere, the stress-differences will become

small at and below the base of the lithosphere. On account of the incompleteness of local compensation, the irregularities and uncertainties of the actual facts of nature, the Gordian knot of a solution may be cut by simply assuming for present purposes the form of diagram given by hydrostatic pressures due to a compensation uniformly distributed. The approximate stress-differences will be given by taking one-fourth of the values given by the hydrostatic pressures. This transfers the problem from the difficult field of zonal harmonics to the simple one of hydrostatics, and perhaps does not introduce errors greater than those involved in the differences between nature and the postulates which form the foundation of the solution by zonal harmonics. This hydrostatic diagram is shown accordingly in Fig. 13.

It is held by the advocates of extreme isostasy, however, that for long-continued stresses the crust is very weak; in other words, the elastic limit is low, and slow plastic deformation readily occurs which tends to dissipate the stress-differences and re-establish isostatic equilibrium. To the extent to which this is true, the real diagram of lateral stresses would approach the hydrostatic diagram here given and measure the forces producing plastic flow.

It has remained, however, for the opponents of the hypothesis of local and nearly perfect isostasy to point out, what is here illustrated graphically, that the extreme theory requires a belief in vertical weakness but lateral strength. If it were not for lateral strength the land-column would crowd against the sea-column, more at the top than at the bottom. Flowing out with a glacier-like motion over the upper part of the sea-column, the land-column would settle at the top and become shorter. This in turn would bring about a vertical elevatory pressure against its bottom, the column would rise, lateral creep would continue with equal pace, and the end result would be a density stratification in which the continental crust would come to overlies the oceanic crust. The limit of such an action would be given by the decreasing surface gradient, this finally becoming so gentle as to stop the glacier-like flow. The lack of such an effect implies of course that the lateral stresses of the outer part of the lithosphere lie within the elastic

limit. Therefore they may be regarded as having not more than a quarter of the value shown in Fig. 13A.

The suggestion of the existence of opposing modifying factors is to be found in conclusions from the previous parts of this investigation—that compensation may be in many places concentrated somewhat in the outer half of the zone as here shown and in other places fade out through a notable distance below. These two variations in the distribution of compensation would modify the stress diagram in opposite directions.

*Modifications of stresses produced by base-leveling.*—Consider next the case of complete erosion to sea-level, as shown in Fig. 13B. The rock from the land-column has been deposited as sediment over the sea-column. As the columns are supposed to act as units the sediment is shown as spread uniformly. The lateral stress diagram beneath the bottom of the sediment shows a rate of decrease the same as in case A, but the value of the hydrostatic stress at any depth is diminished by the sum of the depths of erosion and deposition. The lateral stress now changes in sign at a point *S* and at this depth is a line of no lateral stress. Above this depth the continental segment tends still to spread over the ocean, but less effectively than before; below this depth the oceanic segment now thrusts against the continental crust.

If the ocean water be eliminated from the diagram and base-leveling should bring both columns to a uniform surface, then the neutral depth *S* advances to the surface and the lateral stress diagram in B is just the reverse in value to A. In that case there is no lateral thrust at the surface, but at all depths below there is an excess pressure against the continent reaching a maximum at the bottom of the lithosphere. This extreme case cannot apply to the ocean except for that limited width over which is built out a continental shelf. To the degree to which the weight of this shelf is supported by the ocean crust beyond, the column beneath the shelf would not operate with its full pressures against the land. The case would apply better to the complete erosion of level-topped plateaus situated within a continent.

For the lateral pressure within the lithosphere to become effective in a landward undertow would require a lesser rigidity of the

crust at the bottom than at the top. Such a lesser rigidity may be granted, but it is seen then that the landward undertow would be greatest at the bottom and could not advance above a depth indicated on the diagrams by  $T$ . At this point the stress is of the opposite sign but of the same value as for the state of isostatic balance in case A. If seaward flow did not take place at this level in the first case, landward flow could not take place in the second.

For the extreme case where isostasy is completely destroyed by surface leveling, no water body remaining,  $T$  will rise upward to a depth equal to one-half the depth of the zone of compensation. If the surface of complete compensation be 76 miles deep, this gives a minimum depth of 36 miles. For the undertow to reach this height implies, however, not only the limiting case of complete destruction of isostasy, but a crust only one-half as rigid at depth  $T$  as at the surface and a previous state of expansive surface stress as great as the outer crust could bear. On the other hand, if tangential pressures due to centrospheric shrinkage should co-operate with the stresses tending to restore isostatic equilibrium, underthrust would become more effective below, but overthrust would also become effective above.

The disappearance of isostatic compensation at a certain level means the disappearance of notable heterogeneity in the earth-shell below, as argued in Part V (pp. 446-48). One of the possible suppositions to explain this is to suppose that this shell is weaker than the crust above and therefore the lateral thrust due to an assumed initial heterogeneity would cause a lateral flow, a density stratification, and a resulting disappearance of the postulated heterogeneity. This supposition of a weaker zone finds support in other lines of evidence. Therefore, although some lateral flow at the base of the lithosphere may occur during the restoration of isostatic equilibrium, it is to be expected that the bulk of such flow will be below, for there the substance is more plastic and the lateral stress is throughout at a maximum.

Let attention be given next to the vertical as contrasted to the lateral unbalancing brought in by the destruction of isostatic equilibrium. The land-column becomes lighter, the sea-column heavier, by amounts which are shown in the *vertically lined* stress

diagrams at the base of the lithosphere in case B. Supposing that vertical readjustment of the columns is prevented for a time by the strength of the crust, the vertical stresses will be taken up by a vertical shearing strain along the partition between the two columns. This shear is equal in amount to the difference in total weights of the columns. Let the shear per unit area be called  $s$ . It acts over a surface taken as 122 km. high. Let this height be called  $h$ . The weight of the columns will vary with their breadth in the plane of the drawing. If the breadth of each be taken as  $b$  and the weights per unit area as  $M$  and  $N$  ( $N$  including rock, sediment, and sea-water), then for a cross-section of unit thickness the total difference in weight is  $(N-M)b$  and the total shear is this same amount, provided that the columns are not sustained in part by other boundaries. But the total shear is also  $sh$ . Therefore

$$sh = (N - M)b$$

$$s = (N - M) \frac{b}{h}$$

For narrow columns  $b$  is small, giving to  $s$  a small value and consequently one within the elastic limit. Let  $b$  become broad and  $s$  will then become large and exceed the elastic limit. The *lateral* pressures, on the contrary, are less dependent upon the breadth, and, if the problem were regarded as one of hydrostatic pressures, would be wholly independent of breadth. The formula shows that the broader the columns, the more readily they will readjust by vertical shear between the columns. Now unless failure by vertical shear took place between the upper part of the columns the heavy column would be held up, the light column would be held down, except for the partial effect of sagging in case the columns were very broad. The lateral landward pressure at the base could therefore not become effective. The loaded portion of the crust must fail first by shear or flexure of its upper portion. Whatever be the distribution of strength it would appear then that the primary yielding is the vertical one and the landward force of undertow can become only secondarily effective.

The hypothesis of local and nearly complete isostasy requires that the elastic limit for vertical shear should be very low in order

that narrow columns should be able to rise or sink. This may be illustrated by the following example:

Suppose a region 50 km. in radius possesses a mean departure from isostatic equilibrium equal to 76 m. of rock (250 ft.) and that the surrounding regions are out of adjustment by the same amount but in the reverse direction. This is the maximum area for regional isostasy which in Hayford's opinion is to be expected, and 250 ft. is the mean departure from isostasy as given by him in his Minneapolis address. But in this example the adjacent regions are each assumed to be out of adjustment in opposite directions by this amount and, therefore, the differential load is twice this or 500 ft. of rock. The case is one which he would regard consequently as rather extreme. Now a cylinder 100 km. in diameter and 122 km. deep could not fail through its bending moment, as in the flexing of a beam. It would have to fail as in punching a rivet hole through a metal plate, in other words, by circumferential shear. The shearing stress per unit area is obtained by dividing the total load by the total shearing surface. With the data taken as above this gives  $s = 8.4$  kg. per sq. cm. or 120 lbs. per sq. in. But strong rock at the surface can readily carry a shearing stress of from 700 to 1,000 kg. per sq. cm. (10,000 to 14,000 lbs. per sq. in.). Isostatic perfection to this degree would therefore require the zone of compensation as a whole to be only about one-hundredth as strong under permanent stress as is solid rock at the surface. This calculation alone would tend to show that the loads and areas by which the crust departs from isostatic equilibrium have been much underestimated by the advocates of extreme isostasy.

It should be noted, however, that, following the lines of his rejoinder to Lewis, Hayford would answer that he regarded the landward isostatic flow as taking place within the zone of isostatic compensation and the vertical shear as operating, consequently, through a depth far less than the thickness of the entire zone of compensation. There are, however, a number of inconsistencies in this argument, some of which have already been made evident. Others will appear as a result of the later discussion of this chapter. But it may be noted that even granting this contention—that only the outer third of the zone of compensation was involved—the



unit shearing stress would be multiplied only by two or three and would still imply a weakness in this part of the crust to resist long-enduring shear or bending stresses, its capacity being only 3 or 5 per cent at most as great as is found to exist in surface rocks for stresses of human duration.

*Relief of stress accompanying restoration of isostasy.*—It is seen from the preceding analysis that the movement of the unbalanced columns toward a new state of equilibrium will be partly by vertical shear in the neutral ground between them, but, where the areas are large in comparison with the thickness of the zone of compensation, the easiest mode of yielding may be by flexure, showing at the surface as crustal warping. Both modes of yielding serve to transmit the excess vertical stresses of the heavy and sinking column into the asthenosphere. If the latter be indeed a shell of weakness it will transmit these pressures more or less hydrostatically. The vertical pressure-differences will act within it as lateral pressures making for flow toward the lighter column. It is shown in Fig. 13B that the maximum horizontal stress in so far as it approaches a hydrostatic distribution acts throughout the whole depth of this zone, so that it not only is weaker than the crust above, but is subjected to maximum stress over a greater area. It will yield by flowage therefore either if of small depth and very plastic, or of great depth but more rigid. If the columns are adjacent and narrow as compared to the thickness of the shell of weakness, then the principles of plastic flow would require that the flow be chiefly in the upper part of this shell. If, however, the columns are of considerable breadth compared to the thickness of the asthenosphere, and especially if at a distance from each other, then the principle of least work would determine that the middle strata of this shell should flow the farthest and the whole would to some degree participate. If an imaginary partition were extended downward through this shell as shown in A and B of Fig. 13 this partition would be found warped after the movement as shown in C of the same figure.

It was seen in an earlier part of this discussion that, even supposing deformation became effective by means of the lateral stresses within the lithosphere and without the existence of a zone

of weakness below, still only the basal part below the point *T* would be competent to give a landward movement during the restoration of isostatic equilibrium. But now it is seen that in the asthenosphere the lateral pressures are transmitted with greater amount, from a greater distance, and with a greater cross-section. The zone is one without notable isostatic compensation within it and is presumably more plastic than the basal part of the lithosphere. Therefore there is good reason to believe that the subcrustal undertow is restricted to the asthenosphere.

The forces actually needed to produce flowage would be in reality but a fraction of those indicated in Fig. 13B as existing in the asthenosphere. The reason is that the greater part of the vertical forces is consumed in producing flexure and shear in the lithosphere. Only a residuum is needed to produce a slow plastic flow in the shell below. For that reason broken lines are used in that part of the stress diagram. The energy consumed within the lithosphere by its deformation will be nearly independent of the breadth of the columns; it will actually tend to become somewhat less with breadth because flexure on large radii will be favored. The energy consumed in the asthenosphere will, on the other hand, increase with the breadth of the columns, but will be spread over a greater area. The temperature effect due to the absorption of energy would appear to be a minor factor, for it cannot exceed that energy which is supplied by the average vertical stress-difference multiplied by the vertical distance moved. The average vertical stress-difference will be the mean between that at the beginning of movement and that residual stress remaining after the movement is completed.

In determining the scale of the diagrams of Fig. 13 the following data were chosen. The land-column was taken in A as having a surface elevation of 1,000 m. and a density of 2.70; the sea as 3,000 m. deep, and the rock below as possessing a density of 2.77. The sea-water has a density of 1.03. These relations give an isostatic balance at a depth of 122 km. In B, erosion of the land to sea-level is supposed to have taken place and the sediment spread with same unit weight over the sea-column that it had as

rock upon the land. These relations give a depth of 54 km. to *S* and 88 km. to *T*.

It should be repeated, however, in closing this topic, that the solutions here given are approximate only and assume that isostatic compensation results in lateral stress-differences which show the same distribution of forces as a diagram of hydrostatic pressures, differing only in magnitude. The writer is inclined to think that the actual facts of nature call in most cases for some depression in depth of the critical points beyond those here shown. Especially is there likely to be under the margins of a continent in isostatic equilibrium some permanent lateral stress-difference within the asthenosphere, due to the compensation above and tending toward a landward undertow. Upon the unbalancing due to erosion and sedimentation this would cause the lateral stress-differences within the asthenosphere to rise more quickly to the low elastic limit and permit more readily than would otherwise be the case a regional readjustment toward isostasy.

#### RELATIONS OF UNDERTOW TO THE ZONE OF COMPENSATION

*Present status of the problem.*—The causes of vertical movements Dutton<sup>1</sup> made twofold. He clearly distinguished on the one hand between those internal forces leading to expansion or contraction, which tend, by producing changes in density, to create isostatically a new surface relief, and, on the other hand, those isostatic readjustments following erosion and sedimentation, readjustments which tend not to make a new, but to restore the older, relief. Folding he regarded as unrelated to the former, as a result of the latter. He had shown earlier (in fact, he had the honor of being the first to show) that the time-sanctioned hypothesis of cooling as a cause of crustal shrinkage and consequent mountain-making was inadequate to account for either the distribution or amount of folding.<sup>2</sup> From this he was led to regard folding as due, not to any kind of contraction, but as a compressive movement of one section

<sup>1</sup> "On Some of the Greater Problems of Physical Geology," *Bull. Phil. Soc. Wash.*, XI (1889), 51-64.

<sup>2</sup> C. E. Dutton, "A Criticism upon the Contractional Hypothesis," *Am. Jour. Sci.*, VIII (1874), 113-23.

of the crust against another, presumably offset by tension in some other region. Dutton's argument is that the crust beneath the plateau is unloaded by erosion, that the crust beneath the basin is loaded by sedimentation. An isostatic movement, rejuvenating the relief, must, by causing the overloaded basin to settle, produce a squeezing-out of matter beneath the sinking area, and a crowding-in of matter beneath the rising area. The surficial movement of sediment is from the high area toward the low. The deep-seated movement is from the low toward the high. Thus the cycle becomes completed and the mass of matter above the level of complete compensation remains the same in each column. The seaward movement of the sediment, as a frictional resistance against the river bottoms, produces only an insignificant drag, but the return subterranean movements by viscous or solid flowage must produce a pronounced drag upon the crust in the direction of the rising region. Dutton's reasoning is clear, but the effectiveness of the action rests upon several assumptions. First, it omits the influence of the surface relief and the degree to which that tends to a lateral spreading movement from the high toward the low regions. Secondly, it postulates a low rigidity to the crust, as he in fact notes. Thirdly, it involves the conception of a strong undertow fairly near the surface in order that the crust above may be too weak to resist the viscous drag. As there were little quantitative data available at the time when Dutton formulated this corollary of his theory of isostasy he could not have tested the validity of these assumptions, but raised the problem for those who should come after him.

This theory of folding took a somewhat different form in the mind of Willis, as expressed in the concluding chapter of his *Research in China*.<sup>1</sup> This work in many ways is of the very first importance and gives a comprehensive view of the geological history of the whole continent of Asia. As to the nature of the movements, he finds that the continent of Asia may be resolved into positive and negative elements, the former areas tending to stand high, the latter tending to stand low. These tendencies are latent during comparatively long periods of quiet and resultant peneplanation,

<sup>1</sup> Vol. II (1907), Carnegie Institution of Washington.

but become operative during epochs of diastrophism. The compressive movements, on the other hand, have pressed and welded the positive elements together, the axial directions of folding representing the compression of the negative zones lying between.

The cause of the diastrophism Willis ascribes to differences in specific gravity, restricted, according to Hayford's determination, to the outer hundred miles of the earth's body; the vertical movements being chiefly due to isostatic readjustment between the several continental elements, the compressive movements being due to the tendency of the heavier oceanic segments of the earth to spread and underthrust the outer portions of the whole continental mass. This theory of the cause of lateral compression was discussed by the present writer in a review of Willis' work,<sup>1</sup> and the objections stated against it there are in part the same as will be elaborated farther on in the present article.

Hayford took up the same subject in his address, delivered at Minneapolis on December 29, 1910, as retiring vice-president of Section D (Mechanical Science and Engineering) of the American Association for the Advancement of Science, the title of his paper being "The Relations of Isostasy to Geodesy, Geophysics, and Geology."<sup>2</sup> This is a paper of broad scope intended to show how vertical movements not in apparent accord with isostasy and also movements of folding may be explained as secondary results of isostatic adjustment and really in harmony with the hypothesis of nearly continuous movement in a crust of low rigidity and of almost complete isostasy. This part of his theory is essentially the same as Dutton's but is elaborated in greater detail.

Harmon Lewis called attention to the defects in this theory of deformation,<sup>3</sup> but Hayford made a rejoinder, positive and sweeping in its style, to this and other lines of criticism by Lewis.<sup>4</sup>

The names of Dutton, Willis, and Hayford deservedly carry much weight and must be accepted at their face value by geologists

<sup>1</sup> *Science*, N.S., XXIX (1909), 257-60.

<sup>2</sup> Published in *Science*, N.S., XXXIII (1911), 199-208.

<sup>3</sup> "The Theory of Isostasy," *Jour. Geol.*, XIX (1911), 620-23.

<sup>4</sup> John F. Hayford, "Isostasy, a Rejoinder to the Article by Harmon Lewis," *Jour. Geol.*, XX (1912), 562-78.

who have not themselves made a critical study of the problems of isostasy. The arguments which the writer advanced in 1909 against this hypothesis were published under a title which apparently did not call attention to them. The style of Hayford's reply to Lewis is crushing and conveys the impression that Lewis has been completely refuted. It is because of these reasons that the subject calls here for fuller development.

In his Minneapolis address Hayford outlines a theory of the principles of diastrophism which turns upon his conclusion that isostasy is so nearly complete that areas of even limited size average only 250 feet from the level of isostatic equilibrium. He assumes chemical and physical changes to be induced in the crust by the changing load due to erosion and sedimentation. These he thinks are superimposed upon the effects of nearly continuous vertical movements of isostatic readjustment. The vertical movements in turn produce a lateral undertow which is given as a cause of localized heating and folding. Apparently this is regarded as a complete mechanism of deformation since the author raises the query:

Is it at all certain that under the influence of such actions the geological record at the earth's surface at the end of fifty to one hundred million years would be appreciably less complicated than the geologic record which is actually before us? I think that it would be fully as complicated as the actual record.<sup>1</sup>

This theory of folding as the result of subcrustal undertow is illustrated by means of two diagrams. In Fig. 1, the zone of viscous flow from the sinking toward the rising area is placed in the lower quarter of the zone of isostatic compensation. In Fig. 2 it is shown in the middle of that zone, dying out both above and below. Apparently then, as shown by these two different conceptions, the author cited was guided by no definite theory, based upon the mechanics of materials, as to the factors which would determine the depth of this zone of undertow and its relations to the zone of compensation.

Harmon Lewis in his paper on the "Theory of Isostasy" has discussed various aspects of the isostatic theory as developed by

<sup>1</sup> *Op. cit.*, p. 206.

Hayford, and among them this question. Regarding the possibility of folding by means of isostatic undertow, Lewis concludes:

Now, according to the theory of isostasy, compensation would be essentially complete, and if compensation is complete the depth of compensation as determined by Hayford's geodetic work would be as great as 60 miles. Hence, the undertow postulated by isostasy would exist chiefly below 60 miles. It is decidedly questionable that an undertow even much nearer to the surface than 60 miles would cause the observed folding in the upper few miles of the crust.<sup>1</sup>

In regard to this criticism by Lewis concerning the cause of folding, Hayford states in reply:

On pp. 621-22 Mr. Lewis sets forth the argument that there is much geological evidence of horizontal movements in the outside portions of the earth, especially in the form of folding, that the controlling movements of isostasy are assumed to be vertical and hence cannot account for folding, and that the horizontal movement or undertow concerned in isostatic readjustment must be below the depth of compensation and hence so far below the surface as to be very ineffective in producing folding.

There are two fatal defects in this argument as applied to controverting anything that Hayford believes or has written.

First, Hayford has already indicated clearly his belief that the undertow concerned in isostatic readjustment is above, not below, the depth of compensation. In both the figures published in his Minneapolis address the undertow is clearly indicated as being above the depth of compensation and it is also so indicated in the corresponding text. As Hayford puts the undertow comparatively near the surface, where it is conceded that it would be effective in producing folding, the existence of extensive folding is a confirmation, not a contradiction, of his theory of the manner in which isostatic readjustment takes place. It is certainly not fair to hold Hayford responsible, either directly or by inference, for any theory which someone else may believe which involves an undertow situated entirely below the depth of compensation. Mr. Lewis apparently believes such a theory.

Second, the movements which produce isostatic readjustment are necessarily horizontal, not vertical. If two adjacent columns of the same horizontal cross-section extending from the surface to the depth of compensation have different masses the readjustment to perfect compensation must involve a transfer of mass out of one column, or into the other, or from one to the other. In any case the transfer must be a horizontal movement. Hayford has already shown in print more than once that he understands that vertical movement alone does not produce isostatic readjustment. Moreover, a careful reading

<sup>1</sup> *Op. cit.*, p. 622.

of his Minneapolis address will certainly show that he believes that the total amount of material moved horizontally during isostatic readjustment, and especially the total number of ton-miles of such movement, is vastly in excess of the corresponding quantities concerned in the vertical components of the movement which takes place. Hence the folding and other abundant evidence of past horizontal movements observed by geologists confirm Hayford's hypothesis as to the manner in which isostatic readjustment takes place, instead of conflicting with it as Mr. Lewis' article would lead one to think.<sup>1</sup>

The present writer, however, believes with Mr. Lewis in the theory that an undertow must be essentially below the zone of compensation and is incapable of producing surficial folding. The reasons have been given in part in the consideration of the stress-relations, as they would exist under the hypothesis of extreme isostasy. But there are other reasons why the subject should be discussed in further detail. One reason is that, if Lewis is right on this point and Hayford wrong, it is desirable that this should be made clear, in justice to Mr. Lewis as well as to the subject. The other reason is that here in reaching a conclusion we can advantageously pursue a method of exclusion. By showing that isostatic undertow cannot take place within the zone of compensation, for various reasons besides those discussed in the stress diagrams, we reach the conclusion that it must take place in a level below that zone. Furthermore, by noting the conditions which would hinder lateral flowage we may arrive at a conclusion as to those which must exist to greater or less degree in order to permit it.

*Objections against undertow in the zone of compensation.*—The pressures which occur during a state of isostasy and after the destruction of that condition have been discussed. It was seen that the pressures making for the undertow necessary to restore isostasy were greatest at the bottom, but, more especially, below the bottom of the zone of compensation. The possibility remains to be considered, however, that perhaps the distribution of the rigidity of the crust more than offsets the distribution of pressures. Suppose the middle of the zone of compensation should be very weak and the crust at and below the bottom be very strong. Then,

<sup>1</sup> *Op. cit.*, pp. 573, 574.



if the restoration of isostasy was deferred until assisted by strong tangential pressures due to centrospheric shrinkage, it might be held that isostatic undertow could take place within the zone of compensation and between *S* and *T* of Fig. 13B. If, furthermore, compensation should be not uniformly distributed but taken as largely concentrated in the upper part of the zone of compensation, which however is contrary to the Hayfordian hypothesis, then the forces making for undertow may correspondingly rise in the crust. For these reasons it is seen that the previous argument from the distribution of pressures is not final and that the physical conditions involved in lateral flowage must also be considered.

The only positive reason which has been advanced for seeking to place the undertow within the zone of compensation is in order to utilize its viscous drag as a cause of folding. To become effective the drag must be strong, the crust above by contrast weak and therefore thin. The crumpling pressure on the *surface* of the crust cannot be transmitted directly from the sinking area, as is shown in Fig. 13, since the thrusting force is greatest at the bottom. It must be supposed to arise from the viscous drag of the undertow. But viscosity decreases the hydrostatic head with increasing distance from the source. Therefore, to permit a viscous flow at a distance from the source of pressure implies a mobility within that level of the crust which would make it wholly incapable of carrying the stresses necessary to maintain its own isostatic equilibrium. Therefore this level, by the very terms of the general conception of isostasy, would become the bottom of the zone of compensation.

As another mechanical defect of the theory under review, it is to be noted that the section of undertow taken by Hayford as in the middle of the zone of compensation is not given as involving more than half of that zone. This is as if a viscous fluid were transmitted through a pipe in which the cross-section of pipe and fluid were equal. To assume that the fluid is free to escape into a region of less pressure at the far end and yet gives such a frictional resistance against its walls as to be able to crumple up the pipe is to assume that the two are of the same order of strength. The materials of pipe and fluid might almost be interchanged.

In such viscous flow the tendency would be for a swelling and bursting to appear at the near end rather than a through flowage with a crumpling of the pipe at the far end.

Finally, the greatest theoretical difficulty is encountered when it is sought to transmit matter from beneath the regions of oceanic marginal sedimentation to beneath the regions of a continental interior. Either directly or indirectly there must be a subcrustal transference going forward all the way between these distant regions; for example, from beneath the Mississippi and Colorado deltas to the fields of erosion in the Rocky Mountains, if a condition of even approximate isostasy is to be maintained throughout. This does not mean of course that an individual ton of plastic rock is transferred a thousand miles to balance a ton of sediment. Each subcrustal unit may be transferred only a mile, but it involves a subsurface movement of matter all the way from the regions of sedimentation to the regions of erosion.

Now this implies a *continuous pressure-gradient*, and even under the conception of great crustal weakness, a pressure-gradient which could fold the weak cover-rocks would be far higher than that needed for the movement of a continental glacier. Any large degree of viscous resistance in the zone of undertow would therefore require, in order to initiate movement, an enormous defect of isostasy under the distant continental interior, an enormous excess under the marginal oceans. After a rejuvenative movement had started, it would be slow, the frictional and deformative resistances nearly balancing the deforming force. Therefore inertia of the moving mass could not carry it appreciably beyond the point where the moving force, weakened by loss of head, would just balance the resistances to further movement. It would be expected, in consequence, that a residual pressure-difference would remain, even after a period of restorative isostatic movement. But an inspection of the map of New Method anomalies given in Part II, p. 153, does not show any such anomaly gradients as would comport with this expectation. A vast region of the continental interior extending from Lake Superior to the Rio Grande and westward to beyond the front ranges of the Rocky Mountains shows average positive anomalies, indicating an excess of matter, not a

deficiency. To the westward is a broad region of average negative anomaly reaching a maximum at centers near the Pacific coast and no marked excess is shown near the mouths of the great rivers. Such a lack of regional relations would appear to show that the anomalies are due much more to local loads and irregularities upon and within the lithosphere, and to bowings due to great compressive movements unrelated to isostasy, rather than to the existence of an isostatic gradient leading from the ocean borders to the interior fields of great erosion. Therefore either the idea of strong viscous drag by undertow or else the very doctrine of isostasy—one or the other—must be abandoned. But it has been seen that if undertow exists in a comparatively plastic stratum, then that physical condition will cause it to be the bottom of the zone of compensation. Thus the application of every pertinent engineering principle reduces the initial hypothesis of surface folding by isostatic undertow, and, especially by undertow within the zone of compensation, to an absurdity.

*Undertow restricted to a sphere of weakness—the asthenosphere.*—All of this accumulative argument has not been advanced merely to show that a certain view is wrong. Rather has it been the intention to prepare the ground for what would appear to be a sounder theory of the mode of maintenance of isostatic equilibrium.

As for the basis of that theory, Schweydar, from the mathematical analysis of the measurement of the tides in the crust by means of the horizontal pendulum, has found that they are in accord with the assumption of the existence of a slightly plastic zone about 600 km. thick beneath a more rigid crust 120 km. thick.<sup>1</sup> It would appear that the geodetic evidence of isostasy points also toward the existence of such a thick and somewhat plastic zone beneath the more rigid lithosphere. It gives no knowledge of the exact thickness or depth, but for convenience the figures given by Schweydar will be assumed. It is a matter of importance to note however that, although the quantitative limits are uncertain, the suggestions given both by the tides and by isostatic

<sup>1</sup> "Untersuchungen über die Gezeiten der festen Erde und die hypothetische Magmaschicht," *Veröffentlichung des k. k. Preusz. geodät. Institutes*, Neue Folge No. 54, Leipzig (1912, B. G. Teubner).

compensation point to a zone of weakness much deeper and thicker than the figures which have customarily been taken as a probable depth of origin of magmas. The latter however rests upon uncertain extrapolation, whereas the figures for the limits of the asthenosphere, although of no exactness and perhaps 20 or 50 per cent from limits which finally may be chosen, have at least been determined by more direct evidence. In such a thick shell of weakness, the readjustment, after an erosion cycle, of a continental interior to isostatic equilibrium would require but very little viscous shear and but little lateral movement.

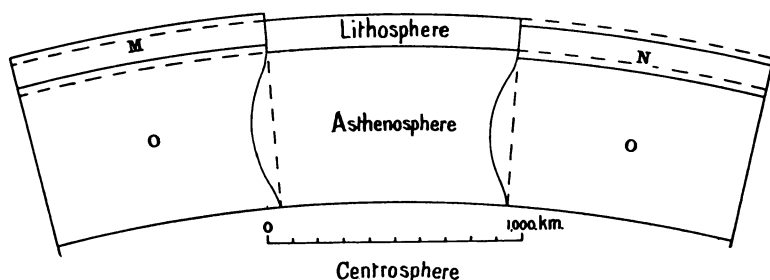


FIG. 14.—Diagrammatic vertical section of the crust, to show nature of undertow in the asthenosphere necessary to restore isostatic equilibrium in a positive interior continental area after a cycle of erosion. Effects of a vertical movement of 0.5 km. exaggerated 60 times. Asthenosphere grades into contiguous spheres and best limitations in depth are not known.

To give quantitative visualization to this conclusion Fig. 14 is drawn. Suppose a plateau area 1,000 km. wide in a continental interior to be separated from the region of sedimentary deposit by an intermediate region 1,000 km. across. Take a section 1 km. wide through these regions. Let an erosion cycle cause the removal on the average of 0.5 km. of rock from this area to be deposited over an equal area of sea-bottom. Then, during an epoch of diastrophism, assume complete recovery of isostatic equilibrium by undertow in a sublithospheric zone of weakness 600 km. thick. The vertical section of rock eroded is 500 sq. km. in area. As we have chosen a width of section of 1 km. we may also speak of this as the volume, 500 cu. km. To restore the mass of this column, 500 cu. km. must be added to it and flow past the vertical line which bounds it on the seaward side. As this zone of

flow is 600 km. deep, the actual lateral movement, if all depths move equally, will be but 0.83 km., since  $0.83 \times 600 = 500$ . If the flowage is supposed to increase regularly from top and bottom to the middle the movement of the middle layer would be 1.66 km. A previously vertical line 600 miles long through this asthenosphere would then be bent at the middle by this amount and its two halves make angles of  $0^{\circ}19'$  with the vertical. Each layer a kilometer thick would move horizontally 5.6 m. with respect to each adjacent layer of kilometer thickness. These figures bring out the insignificant degree of the plastic deformation in such a deep zone which is needed to restore isostatic equilibrium, even for a large interior continental area after erosion amounting to two-thirds of the present average elevation of the North American continent.

As a matter of fact the cross-section of the plastic deformation would not be a triangle, but a sinusoidal curve, so that the maximum linear flow for thickness of 600 km. would be between 0.83 and 1.66 km.

This illustration makes it clear that the isostatic rejuvenation of continental interiors as well as of the margins, which meets such grave difficulties under the hypothesis of a thin and shallow zone of isostatic undertow, is eliminated by adopting the hypothesis of a thick and plastic sublithospheric shell, such as has been found to be suggested by independent evidence.

The idea of folding as a result of isostatic undertow definitely may be abandoned, but the absence of a notable isostatic gradient has some further significance. It is seen from Fig. 14 that if the fields of great erosion and deposition are within a few hundred kilometers of each other the rejuvenative undertow, under the laws of stress distribution in plastic bodies, would involve mostly a limited tract in the outer part of the asthenosphere; whereas, if the undertow must extend over distances of 1,000 km. or more, then the whole depth of the asthenosphere will become involved. The amount of stress-difference and of plastic shear per unit of volume may therefore be no greater in the one case than in the other. Especially, if the middle of the asthenosphere is its weakest part, a movement generated by areas large enough to involve the whole of this zone would go forward under less stress-difference per unit

of area than for more local adjustments. The absence of a notable continental gradient is suggestive therefore of a deep zone of weakness, least resisting in its central portions, and of very marked plasticity in comparison with the rigidity of the lithosphere above. This does not involve, however, the conception of a truly fluid zone, but merely that of a comparatively plastic solid.

The existence and nature of this zone of weakness is seen to enter vitally into the theory of isostasy and must of course bear with equal importance on other branches of terrestrial dynamics as well. It is proposed therefore to elevate it to equal rank with the other shells of the earth and to name it for that quality which, from the standpoint of diastrophism, is its most significant feature as compared to the zones above and below. This is its inability to resist stress-differences above a certain small limit. Its name, therefore, is the sphere of weakness—the asthenosphere.

*[To be continued]*